# Fault Localization in Medium Voltage Networks with Compensated and Isolated Star-point Grounding

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*Abstract*—**This paper presents the experimental investigation of a fault localization algorithm in a network with compensated or isolated star-point grounding. The paper first discusses the theoretical background of the method and then the conclusions drawn from the discussion were tested using a complex network structure (NETOMAC®) with the support of models developed in MATLAB®. Finally, the complete method is proposed and its usability confirmed.**

***Keywords: isolated and compensated networks, protection systems, fault localistation, network simulation***

## I. Introduction

The purpose of the medium voltage network is to distribute electrical power from the high voltage transmission stage to the "big" decentralized customers. Energy flow used to be in one direction only, because the power sources were centralized. Due to the fact that today´s power sources are more distributed, with a significant and increasing number of the energy sources connected to the distribution network (bidirectional energy flow), the protection of these networks has become more complex. The healthy state of the medium voltage network not only has an influence on each customer but also on the stability of the entire system. Therefore, an unhealthy network state must be eliminated as quickly as possible. Since cables are predominant in medium voltage networks, the capacitance is large. These networks are operated with compensated or isolated star-point grounding, depending on the level of capacitive current. The advantage of compensated or isolated star-point grounding is the ability to maintain service during a single pole to ground fault, because it is not necessary to disconnect the defective network area within a short time after a single ground fault occurs [1]. Since the single pole to ground fault introduces severe asymmetry in the voltages (e.g. magnitudes of two unaffected phases are significantly higher), the fault location needs to be detected in order to restore the system to normal operation. In practice this requires a significant technical effort. Because of this, simpler methods are needed. In this paper one of the methods for localizing faults in networks with compensated or isolated star-point will be presented. The method is based on the analysis of the apparent power of the measured zero sequence components [2]. The paper discusses the basis of the proposed technique in detail. The procedure can be implemented in devices with a communication interface (e.g. differential protection). By means of the transfer of additional information, such as the sign of the zero-sequence apparent power, the defective network area can be detected. It provides robust performance, also for highly complex systems (e.g. ring or mashed structure), which will be analyzed in this contribution. The described method decreases the effort required to localize the faulty line. Therefore, practical use of the investigated procedure is confirmed. The investigations discussed in the paper are based on numerous simulations of the single pole to ground fault in typical networks with isolated / compensated star-point. These simulations were carried out using the network modeling program NETOMAC®. The acquired results were used as input for the calculation models implemented in MATLAB/ SIMULINK®. The created models allow for the detailed investigation of the different influencing factors on the proper detection of the defected network area. The paper presents systematic investigation methods for the detection of the fault location in networks with compensated/ isolated star-point and is closely related to practical applications. The described procedure was registered as a patent.

## II. Method Description

### A. Zero Sequence Apparent Power Analysis

As previously mentioned, one of the methods that can be applied to support fault localization in a compensated or an isolated network is based on the analysis of the sign of the zero sequence apparent power. The zero sequence apparent power can be expressed as follows:

$$\underline{S}_0 = \underline{U}_0 \cdot (\underline{I}_0)^* = S_{0(\mathrm{Re})} + jS_{0(\mathrm{Im})}, \tag{1}$$

where $\underline{S}_0$ is the zero sequence apparent power, $\underline{U}_0$ and $\underline{I}_0$ the zero sequence voltage and current respectively. The complex zero sequence apparent power $\underline{S}_0$ consists of two components: real part (real power) and imaginary part (reactive power). This zero sequence apparent power can be measured by the protection instrument with the available voltage and current measurement analog inputs. Depending on the network character (compensated or isolated network) either real or imaginary components must be analyzed. In this section, the theoretical consideration will be carried out.

### B. Isolated Network

Isolated networks operate without grounding the supply side. This type of network is particularly applied at the middle voltage level, at the distribution stage of the energy system. The isolated networks are predominantly constructed from cables, so that the capacity is relative large. Since the capacity amount in the network has an influence on the short circuit current (a single pole especially influences the earth short circuit), this network type is designed in such a way that the fault current is below the threshold of the self electric arc cancellation and the single phase fault doesn't transfer into other phases [3]. As a result the isolated system can work without separating the defective network area from its operation. This is especially useful if the disturbed network region contains the energy sources that can contribute to energy interruption if separated from the system.

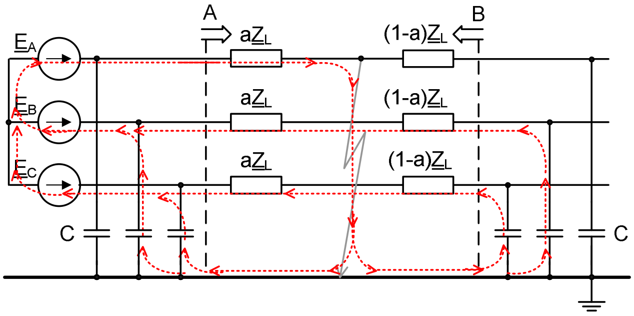


Figure 1. Simplified isolated network during single pole to earth short circuit

In Figure 1 the simplified isolated network is presented. It was assumed that protected line is situated between points A and B and the entire capacity of the network is placed on both line ends. Moreover, for simplification reasons the network is supplied from one side only. For our consideration, the fault is placed at the protected line in the position defined by a, dividing impedance of the defective phase line on impedances $a\underline{Z}_L$ and $(a-1)\underline{Z}_L$. As can be noted the fault flowing current closes the electrical loop through the line capacity C of non-defective phases as well as through the ground. Thus, an earth current with a predominately capacitive character appears, and is represented by zero sequence of symmetric components. Assuming that the line impedance $\underline{Z}_L$ is low, this short circuit current depends on the capacity amount in the network only. The zero sequence currents considered from both measurement points A and B have the same direction and their level depend on the capacity amount placed at side A and B. Thereby it can be concluded that when analyzing the zero sequence power flow direction the fault direction can be detected as well. This is shown in an example in Figure 2. Generally only zero sequence components can deliver valuable information for detecting fault direction, because load influence can not be neglected for positive and negative sequence. Also, the zero-sequence component has a predominately capacitive character resulting from the significant phase-to-earth capacity. However, this is not the case for a positive or negative sequence. Using the formula from (1) and applying it to an imaginary component (reactive power) only, the following expression can be obtained:

$$\mathrm{Im}[\underline{S}_0] = \mathrm{Im}[\underline{U}_0 \cdot (\underline{I}_0)^*] = S_{0(\mathrm{Im})}\,. \qquad (2)$$

Since the measurement system for the protection device has defined directionality for current (to the line) and the voltage is measured from earth-to-phase, the positive reactive power is detected for faults in a forward direction. The current level can not be explicitly used to locate the fault because it depends on the capacity amount, which is unknown for today's highly complex electrical system. If the fault is located outside the line, either the A or B measurement device will acquire negative reactive power and the other one will detect positive power [2]. Therefore, by analyzing the sign of the reactive power for zero sequence it can be determined whether the protected line is defective or not.

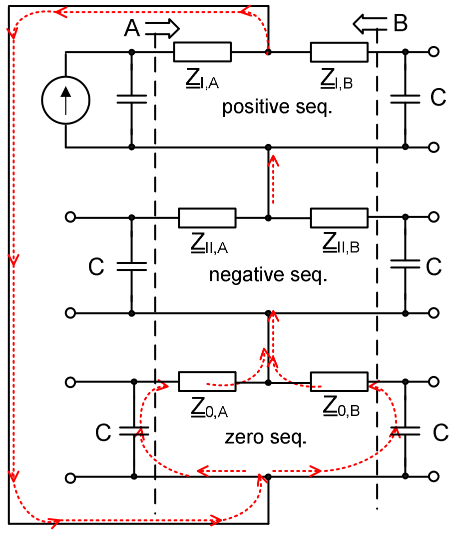


Figure 2. Simplified isolated network during single pole to earth short circuit in symmetrical components representation [4]

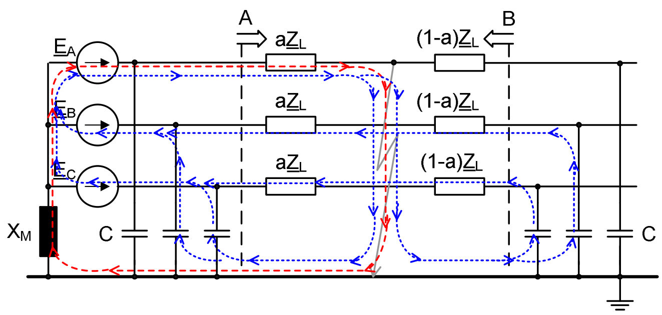


Figure 3. Simplified compensated network during single pole to earth short circuit

## C. *Compensated Network*

For a network with a high capacitive current the short circuit can not be cancelled by itself and the fault can transfer on to other phases. In order to reduce this current an additional inductive coil is applied at the star-point and this point is additionally grounded as shown in Figure 3. This type of electric system is called a compensated network [2]-[3]. Introducing the appropriately fitted inductive component into the network allows the parallel resonance to build up between network capacity and the inductive coil that is active especially during a single-pole to earth fault. In Figure 3 the propagation pathways for capacitive and inductive currents in the network are presented. Due to resonance phenomena, the current at the location of the short circuit is close to zero and the network can be further operated. As can be noted, in this case the reactive power can not be used for detection of the fault direction because for point A the zero seq. reactive power is inductive and for point B it is capacitive. The full compensation appears at the short circuit location, at which capacitive current is balanced by the inductive component [3]. How to detect the fault direction will be explained based on the single pole to earth short circuit model represented with the help of symmetrical components [4]. In Figure 4 this representation is shown. Similar to an isolated network the positive and negative sequence can not be used. The influence of the load and high phase-to-earth capacity on the short circuit current is not easily predictable for these two components if the fault position is unknown. Moreover for negative sequence, in the case of full compensation, relative low signals for current and voltage appear. Also the zero-sequence component seems to be not useful, because as mentioned, one side sees the significantly inductive and the other side see the capacitive zero sequence current. The solution for that is an analysis of the real part of the zero seq. apparent power like expressed here:

$$\mathrm{Re}[\underline{S}_0] = \mathrm{Re}[\underline{U}_0 \cdot (\underline{I}_0)^*] = S_{0(\mathrm{Re})} \cdot \qquad (3)$$

Side A can measure then the losses resulting from resistance of the inductive compensation coil $X_M$ and resistance of the left network part. Side B detects the occurred losses in the right network part. However from a measurement point of view this task seems to not be simple, because the losses are not so big as compared to the appeared reactive components. The measurement of the real zero seq. power is then possible if the instrument transformer for the earth current, which is highly sensitive and accurate, is applied. It is a very important requirement in order to use the real apparent power to detect the fault direction in compensated networks [2].

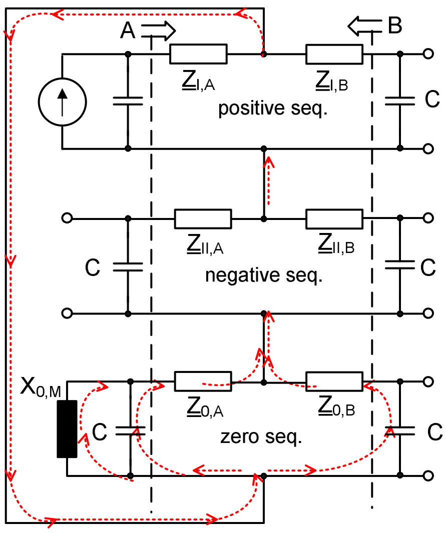


Figure 4. Simplified compensated network during single pole to earth short circuit in symmetrical components representation

Similar to the case of the isolated network, the level of the resistive current can not be used for fault localization, because the fault position is unknown and, therefore, the resistive losses are unknown as well. Only the sign of the zero seq. power can be taken into account as a valuable indicator for the fault direction. This is possible because the earth current directionality is defined and realized mostly in a line direction. Hence, the following conclusion can be made: if the fault is situated in a forward direction the real zero seq. power is negative; if the fault is localized in a reverse direction then the gathered power is positive [2]. For the fault outside the protected line one device will measure the positive and another the negative zero sequence power. The fault can be fully localized by using a communication interface between the two devices.

## III. Method Testing

To test the two methods an electrical middle voltage system with significant complexity was constructed. The network creates a ring structure that is supplied from two independent sides. In addition, a parallel line is applied to heighten the network complexity. Four different load characters were connected to the system with the goal to conduct a sensitivity investigation of the method during load condition changes. The network with single pole to earth short circuits of different localizations was simulated in the NETOMAC® software (Figure 11). It was assumed that the protected lines are L_1, L_2 and L_8. The acquired simulated results in Comtrade format [5] were applied to the MATLAB/SIMULINK® Software (before Comtrade Reader for MATLAB® was programmed) in which appropriate models to detect the zero seq. power were designed. The SIMULINK® model is presented in Figure 5. Zero seq. voltage and current are necessary to measure the zero sequence power. These two quantities can be acquired using a special instrument transformer or calculated from available phase voltages and currents. The second step is transformation of the time quantities into complex values. This done using the sine and cosine filters designed for fundamental component [6]. In our investigations, simple 20-sample filters (at sampling frequency 1kHz) were used. The complex zero seq. currents and voltages were created from the filtered values and then the powers were calculated. The signs and direction of the fault were detected by comparing the appropriate parts of the zero seq. apparent power, depending on the network character.

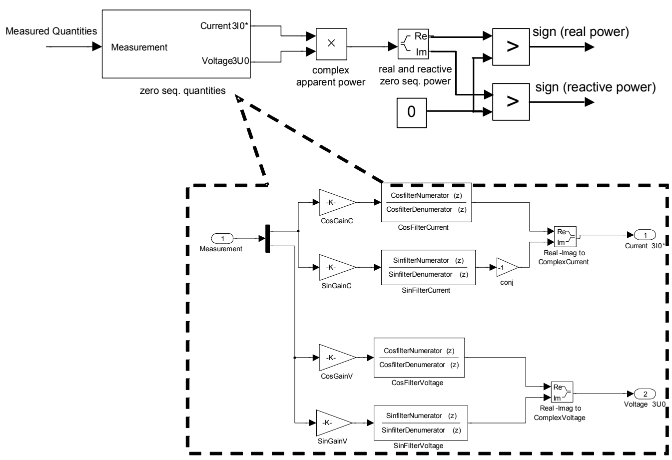


Figure 5. Matlab model for detecting fault direction

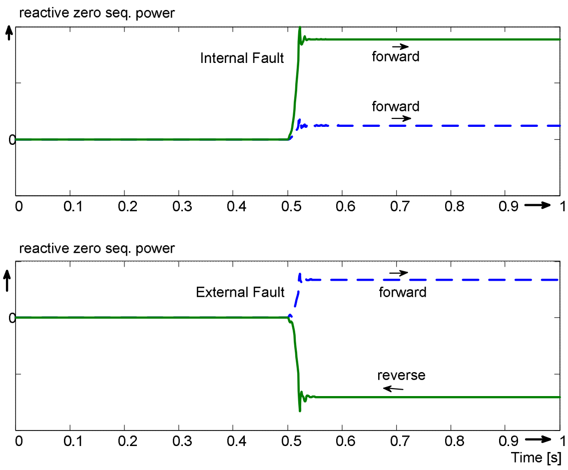


Figure 6. Simulation results from isolated network for two fault localizations

Numerous tests for protected lines L_1, L_2 and L_8 were performed and behavior of the zero seq. apparent power was analyzed. Generally no problems were detected, because the network was characterized by both relatively big phase-to-earth capacity and resistive losses. Due to this fact clear detection of the appropriate part of the zero seq. power was possible. However, it must be mentioned that simulation results do not reflect the pure physical behavior of a real network with a measurement system and serve only as a relatively good approximation. If the system has low capacity or low resistive losses and additional measuring instruments have a significant error, then a strong deviation from the expected results can appear. Therefore, depending on the network design and its parameters, stabilization thresholds must be introduced. This means that the power can not be directly compared to zero, but that some uncertainty area will appear. The examples of the results in an ideal case are presented in Figure 6 and Figure 7 for an isolated and a compensated network, respectively. The protected line is the L_1. In both cases the method responses are correct. In the case of the isolated network for internal fault one side sees more reactive power (entire capacity of the right side) while the left side detects only the capacity of the protected line L_1 to the short circuit place. If the fault were placed close to the measurement point, then the left side could not detect fault direction because the reactive zero seq. power could be close to zero. For the external fault, as expected, one side (left) detects the positive and the other one detects the negative zero seq. power. The difference between these two powers is the accumulated capacity in the protected line.

Similar consideration can be performed for the compensated line with regard to real components. For the internal fault (also in this case the protected line is L_1), the left side uses the losses of the inductive coil and left network part, however the right device detects the losses of the right network side. If an external fault occurs, both devices observe the zero seq. power in opposite directions with the difference of the losses at the protected line.

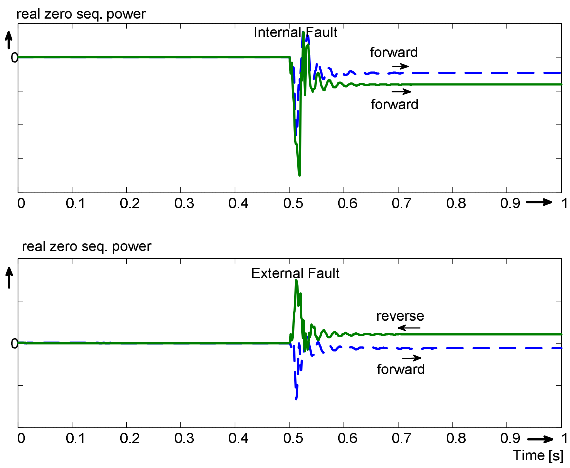


Figure 7. Simulation results from a compensated network for two fault localizations

Analyzing the responses of the apparent power it can be noted that some oscillations may appear. This can be observed especially in the case of the real components for a compensated network, and it results from the building of the resonance between the inductive coil and network capacity with a

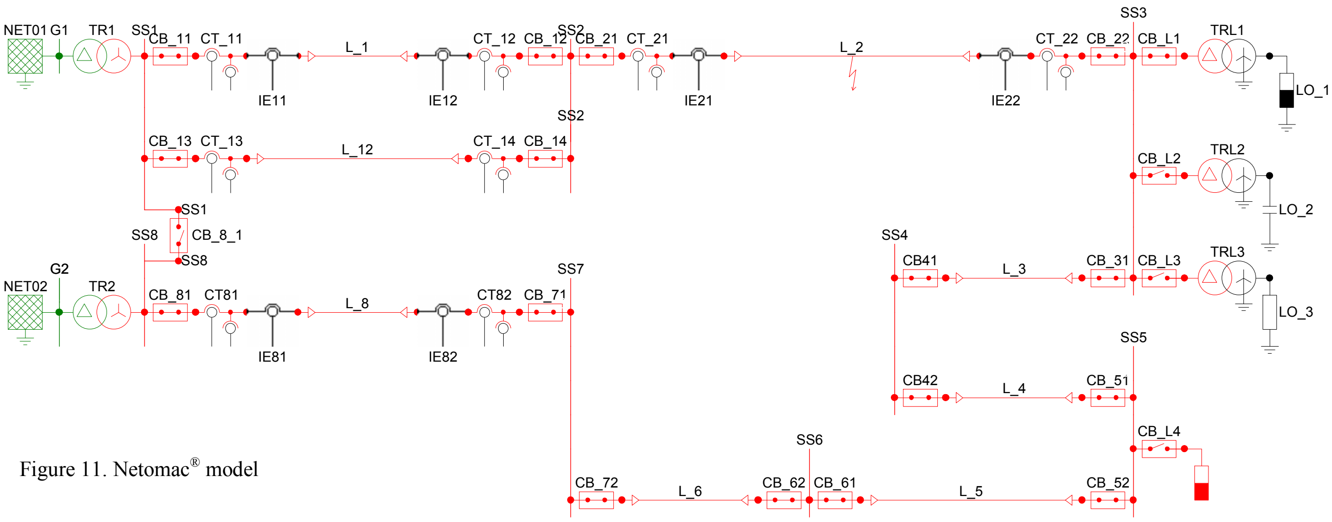


Figure 11. Netomac® model

relatively low damping factor reflected by the network losses. Moreover, the filters for acquiring the apparent power exhibit oscillation after dynamic signal changes that happen after short circuit [6]. Since the oscillation of the apparent power can not be avoided the result of the sign with appropriate delay should be taken into account.

## IV. Fault Localization Algorithm

In sections II and III the basis of the method for detecting the fault direction in isolated and compensated networks was presented. The direction of the fault from one device does not allow for complete localization of the short circuit in the network. Therefore, a communication interface is required to transfer the sign of the apparent power as a binary signal (Figure 8). Such simple communication is not a big challenge for modern protection devices. Furthermore a protection system with an available communication interface can be used, e.g. differential protection. Since the medium voltage networks are very complex such communication can be extended onto the entire system and then the binary signals from devices can be analyzed in the central station. Using such a principle, the additional approach (e.g. switching on the resistance at the star point) for fault searching in compensated and isolated networks is no longer necessary.

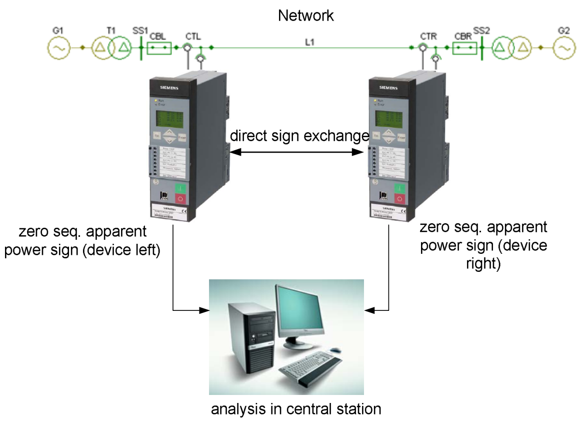


Figure 8. Commucation for fault localizing

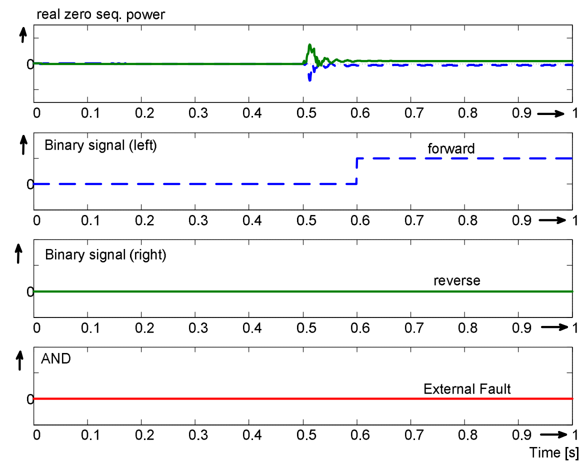


Figure 9. Exchange process of the sign of the zero seq. power for a chosen line in the compensated network for the external fault

The examples of the described method are presented in Figure 9 and Figure 10 for compensated and isolated networks, respectively. After the single-pole short circuit the zero sequence apparent power is measured and, depending on the network character, the sign of the appropriate power part will be sent to a remote device and/or to the central station. For the reverse fault this is the low binary signal. Only for the forward fault, is the binary signal state changed, logically, to high. If the own device and remote device have the same high signal, both instruments enunciate the fault at the protected line. Otherwise an external fault is declared. The enunciation of the fault direction is carried out after a defined time that allows for neglecting the influence of the transient signals on zero seq. apparent power calculation.

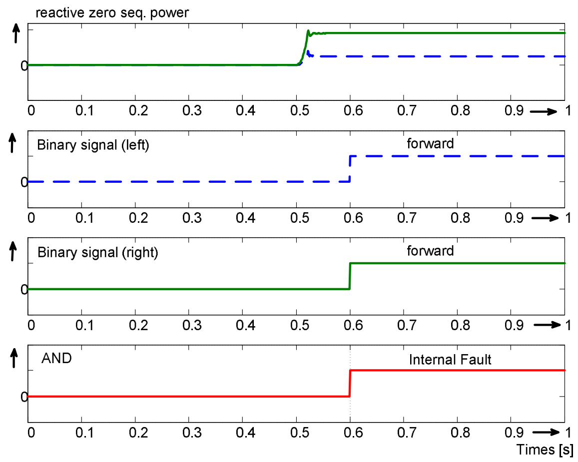


Figure 10. Exchange process of the sign of the zero seq. power for a chosen line in the isolated network for the internal fault

## V. Summary

In this paper the method for localizing a fault in the network was presented. The method is based on analysis of the sign of the appropriate part of the zero seq. apparent power. This method can be applied for isolated and compensated networks, which are very popular on the distribution level. In order to localize the defective line or network area, communication between devices must be realized. Transferring only one binary signal is enough to decide if the fault is located on the protected line or not. The presented method can be applied to highly complex systems. Also, significant penetration of the sources in decentralized form does not affect method performance. No big effort to apply this method in a digital device, for a system with an available communication interface and with implemented voltage and current transformer for zero-seq. component, is needed. The big advantage of this method is a reduction of the effort needed to search for faults by using a common approach with the earth resistance switching.

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